# MULTIPLE PRESSURE MEASUREMENTS ON A PLANETARY ATMOSPHERIC ENTRY VEHICLE FOR ATTITUDE & DENSITY DETERMINATION

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# Introduction

It is important to have engineering data on Thermal Protection System (TPS) and aerodynamic characteristics of the entry vehicles during entry and descent.

Multiple pressures measurements at the heat shield can be used:

- To validate the aerothermodynamic models.
- To infer attitude (angle of attack, sideslip angle history)
- To determine atmospheric characteristics such as the vertical density profile.

# OUTLINE

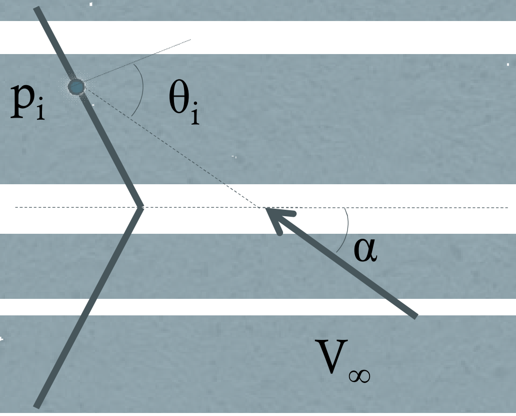
- Methodolgy
  - Attitude Determination
  - Density Estimation
- Validation
  - Earth Entry (EXPERT)
    - Surface pressures from CFD, wind tunnel test
  - Mars Entry (Pathfinder)
    - Theoretical surface pressures using modified Newtonian theory and 3DOF entry analysis
- Conclusions and Perspectives

# Methodology: Cp

θ is the local incidence angle.

## Modified Newtonian flow theory:

$$C_p(\theta) = Cp_{MAX}\cos^2\theta \qquad Cp_{MAX} = \frac{q_c}{q_\infty} = \frac{p_{t2}-p_\infty}{q_\infty}$$




$P_{t2}$ is the stagnation pressure, $p_\infty$ free stream pressure and $q_\infty = 1/2\rho V_\infty^2$ is the dynamic pressure.

## General Solution (Calibration)

$$C_p(\theta) = X + Y\cos^2\theta$$

$$X = \frac{p_{t2}-p_\infty}{q_\infty}\varepsilon \qquad Y = \frac{p_{t2}-p_\infty}{q_\infty}(1-\varepsilon)$$

$\varepsilon = f(M_\infty, \alpha_e, \beta_e,)$ is a parameter taking into account shape and compressibility effects with $\alpha_e$, $\beta_e$ are the effective angles of attacks

$$p_i = (p_{t2}-p_\infty)(\cos^2\theta_i + \varepsilon_i \sin^2\theta_i) + p_\infty$$

# Angle of Attack

Using the pressure model and by taking combinations of three surface pressure differences Γ, we obtain an equation wich is independent of ε, $q_\infty$ and $p_\infty$:

$$\Gamma_{ik}\cos^2\theta_j + \Gamma_{ji}\cos^2\theta_k + \Gamma_{kj}\cos^2\theta_i = 0$$

$$\Gamma_{ik} = p_i - p_k$$

$$\Gamma_{ji} = p_j - p_i$$

$$\Gamma_{kj} = p_k - p_j$$

The last equation can furthemore becomes independent of angle of sideslip by choosing three vertical probes (Φ=0 ° or 180 ° ):

$$\alpha_e = \frac{1}{2}a\tan\left[\frac{A}{B}\right] \qquad \left|\alpha_e\right| < 45^0$$

$$A = \Gamma_{ik}\sin^2\theta_j + \Gamma_{ji}\sin^2\theta_k + \Gamma_{kj}\sin^2\theta_i$$

$$B = \Gamma_{ik}\cos\phi_j\sin\lambda_j\cos\lambda_j + \Gamma_{ji}\cos\phi_k\sin\lambda_k\cos\lambda_k + \Gamma_{kj}\cos\phi_i\sin\lambda_i\cos\lambda_i$$

# Angle-of-Sideslip

Once the angle of attack is determined, we can obtain $\beta_i$ using the pressure differences $\Gamma_{i,j}$:

$$A' \tan^2 \beta_e + 2B' \tan^2 \beta_e + C' = 0$$

$$A' = \Gamma_{ik} b_j^2 + \Gamma_{ji} b_k^2 + \Gamma_{kj} b_i^2$$

$$B' = \Gamma_{ik} a_j b_j + \Gamma_{ji} a_k b_k + \Gamma_{kj} a_i b_i$$

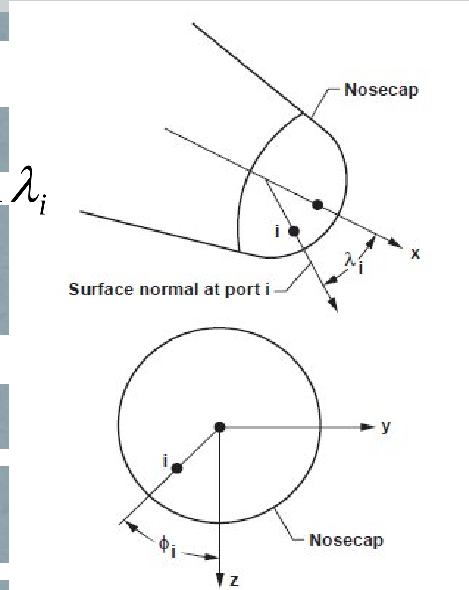
$$C' = \Gamma_{ik} a_j^2 + \Gamma_{ji} a_k^2 + \Gamma_{kj} a_i^2$$

$$a_{\{ijk\}} = \cos\alpha_e \cos\lambda_{\{ijk\}} + \sin\alpha_e \sin\lambda_{\{ijk\}} \cos\phi_{\{ijk\}}$$

$$b_{\{ijk\}} = \sin\lambda_{\{ijk\}} \sin\phi_{\{ijk\}}$$

# Total & Upstream Pressure

Calculate the local incidence angle:




$$\cos\theta_i = \cos\alpha_e \cos\beta_e \cos\lambda_i + \cos\beta_e \sin\phi_i \sin\lambda_i + \sin\alpha_e \cos\beta_e \sin\lambda_i$$

If we neglect the correction factor ε, surface pressure can be expressed as:

$$p_i = (p_{t_2} - p_\infty)\cos^2\theta_i + p_\infty$$

$$\begin{bmatrix} p_{t2} \\ p_\infty \end{bmatrix} = \begin{bmatrix} \cos^2\theta_1 & . & . & . & \cos^2\theta_n \\ 1-\cos^2\theta_1 & . & . & . & 1-\cos^2\theta_n \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ . \\ . \\ p_n \end{bmatrix}$$

Total pressure $p_{t2}$, $p_\infty$ and are linked to the upstream density $\rho_\infty$

# Density Determination

Knowledge of $p_{t2}/q_\infty$ yields $\rho_\infty$ through $q_\infty = 1/2\rho_\infty V_\infty^2$ provided that $V_\infty$ is known

Calorically Perfect Gas($\gamma$=const), (Rayleigh pitot tube formula)

$$\frac{p_{t2}}{q_\infty} = \frac{2}{\gamma M_\infty^2}\left[\frac{(\gamma+1)^2 M_\infty^2}{4\gamma M_\infty^2 - 2(\gamma-1)}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{1-\gamma+2\gamma M_\infty^2}{\gamma+1}\right] \qquad \text{(Eq1)}$$

This equation can be simplify due to the hypersonic velocities ($M_\infty^2 >> 1$):

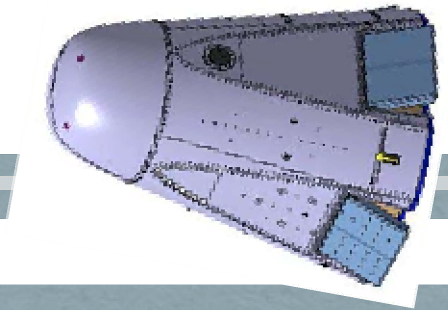
$$\frac{p_{t2}}{q_\infty} = \left[\frac{(\gamma+1)^2}{4\gamma}\right]^{\frac{\gamma}{\gamma-1}}\left[\frac{4}{\gamma+1}\right] = Const.$$

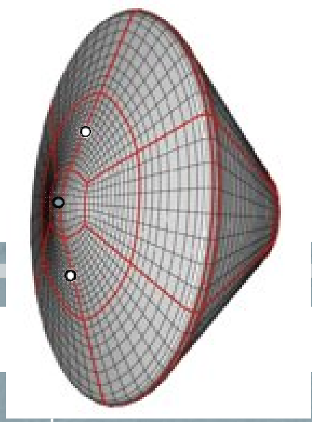
Thermochemical equilibrium ($\gamma \neq$const) (See Olivier and Nieden 2007) :

$$\rho_\infty = \rho_{2E}\left[1-\sqrt{1-\frac{2}{\rho_{2E}V_\infty^2}\left(p_{t2}-p_\infty\right)}\right] \qquad \rho_{2E} = \rho_{t2}(h_{t2}, p_{t2}) \qquad \text{(Eq2)}$$

$$\frac{p_{t2}}{q_\infty} \approx f(V_\infty) \qquad \text{(Eq3)}$$

# Validation





- Earth entry : Expert

$P_i$ given by CFD and Wind tunnel tests.

Positions of pressure probes

| Probe | Cone Angle λ | Clock Angle ϕ |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 45 | 0 |
| 3 | 45 | 90 |
| 4 | 45 | 180 |
| 5 | 45 | 270 |

Mars entry : Pathfinder

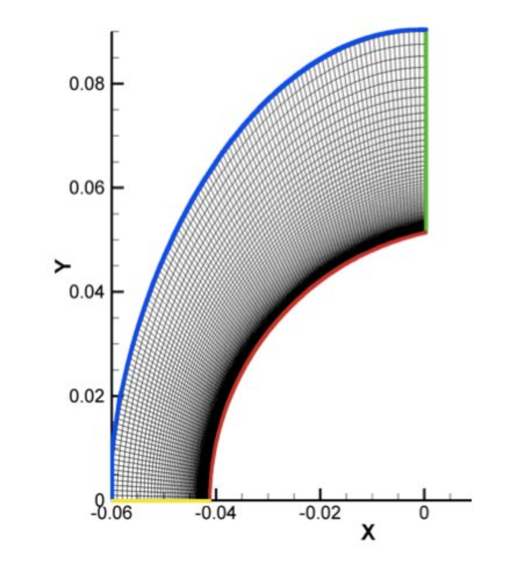
$P_i$ from theoretical considerations (3DOF entry analysis, Modified Newton theory, theoretical measurement error)

Position of hypothetical pressure sensors

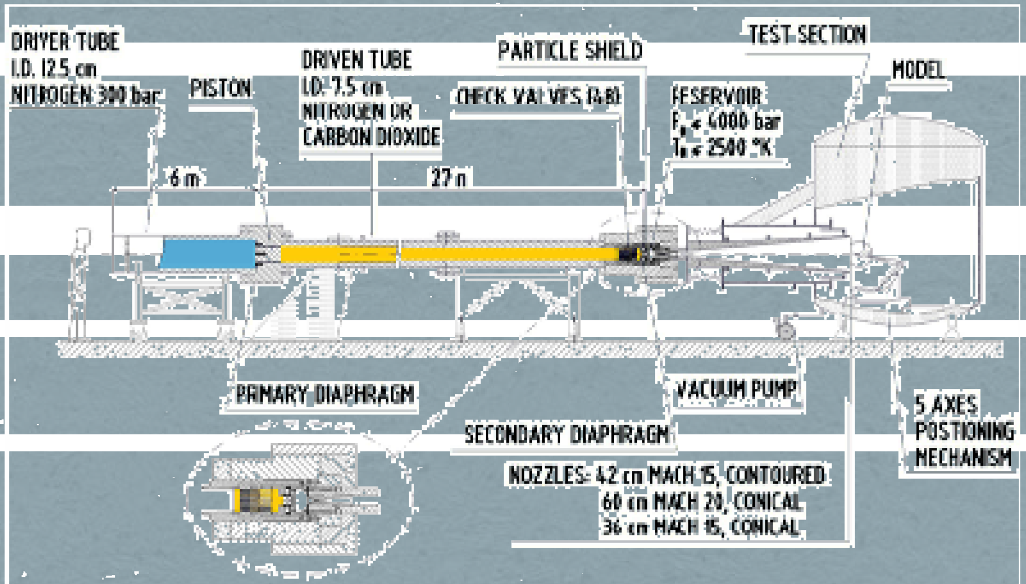
| Probe | Cone Angle λ | Clock Angle ϕ |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0 | 0 |
| 3 | 0 | 180 |

# EXPERT

CFD




Wind Tunnel

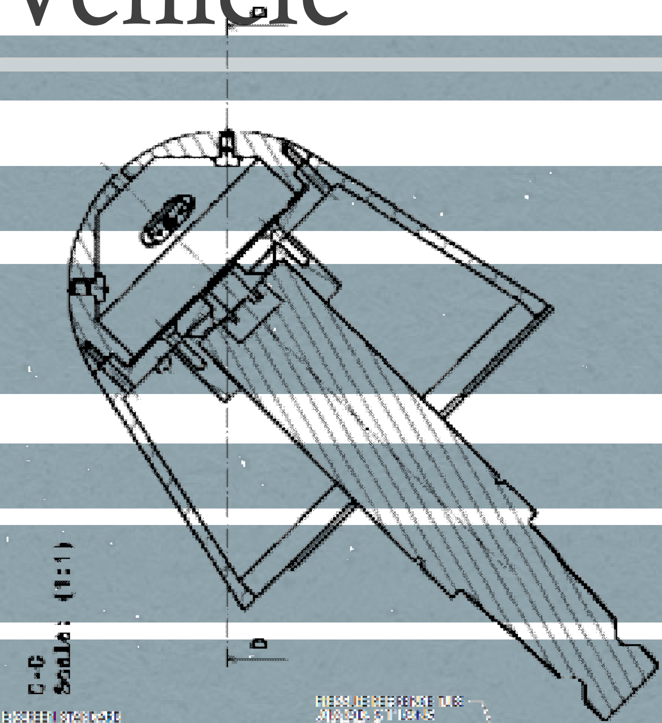


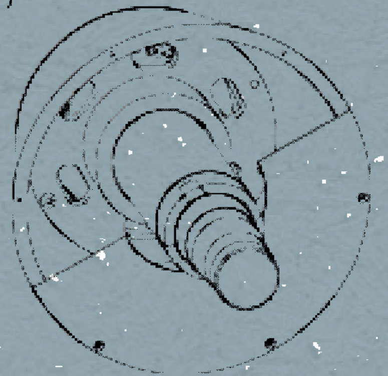

CFD++, Fluent Gambit, Tecplot 360.

BC: inlet in blue, outlet in green, axe of symmetry in yellow, wall in red.

VKI Longshot facility
- heavy piston gun tunnel.

# Wind Tunnel Model
# Expert Vehicle

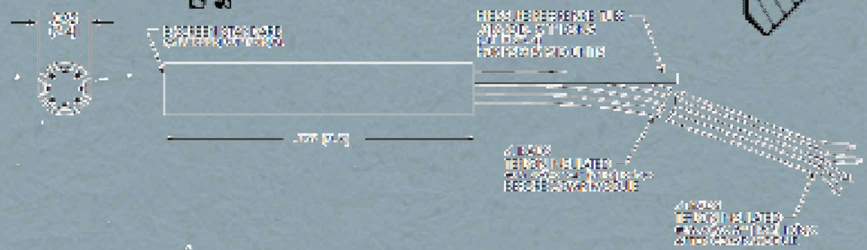
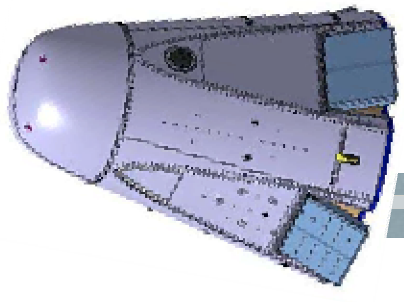



Figure 16: Kulite XCQ-093 series

# CFD RUNS



- Computations were made under the assumptions of
  - Calorically perfect gas (All these tests are performed for the air except for the PG4 case which is performed for the nitrogen (N2)

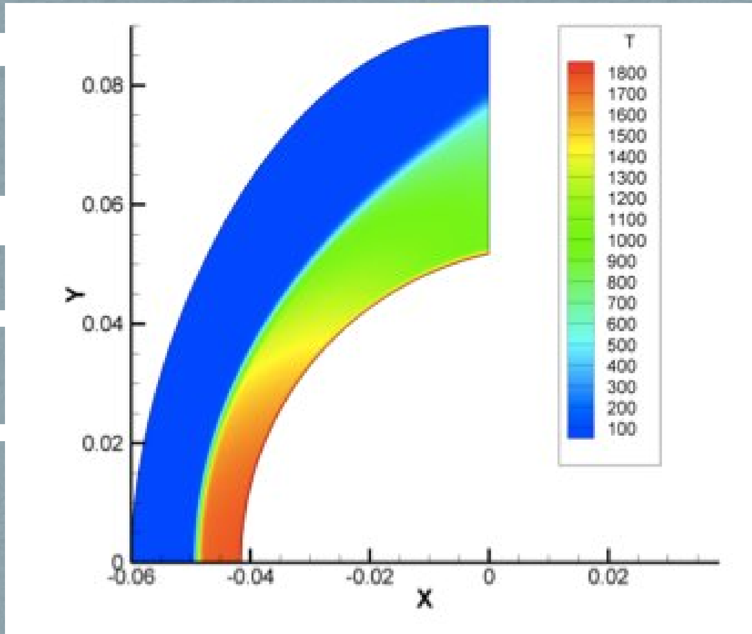
| Test | Velocity U [m/s] | Atm. Pres. P [Pa] | Atm. Temp. T [K] | Mach M [~] | Gas | Comment |
|---|---|---|---|---|---|---|
| PG1 | 590.6 | 9382 | 216.65 | 2 | Air | Flight |
| PG2 | 886.3 | 7596.7 | 216.65 | 3 | Air | Flight |
| PG3 | 2076.47 | 3706 | 219 | 7 | Air | Flight |
| PG4 | 1880 | 140 | 44 | 14 | N2 | Longshot |
| PG5 | 1880 | 140 | 44 | 14 | Air | Longshot |
| PG6 | 4283.62 | 668 | 233 | 14 | Air | Flight |

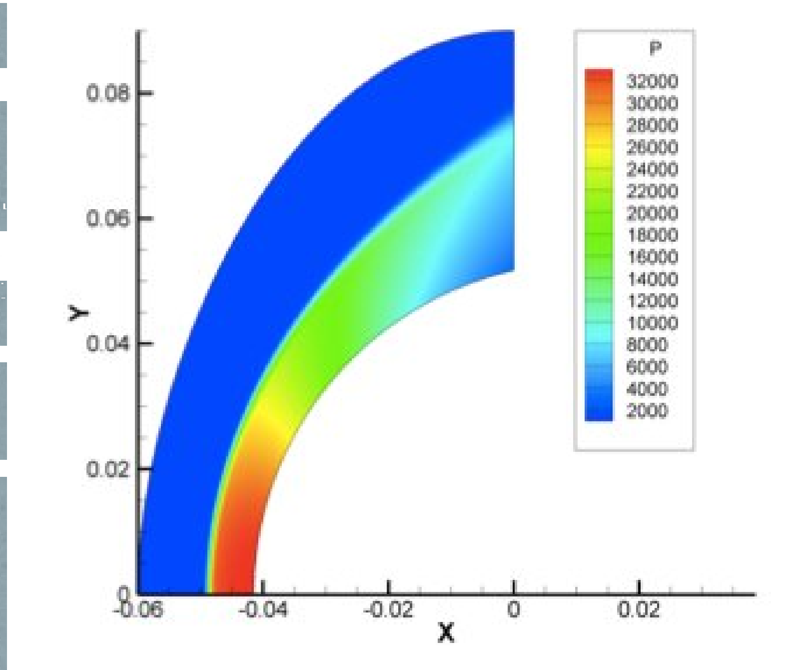
  - Real gases

| Test | Velocity U [m/s] | Atm. Pres. P [Pa] | Atm. Temp. T [K] | Mach M [~] | Gas | Comment |
|---|---|---|---|---|---|---|
| RG2 | 886.3 | 7596.7 | 216.65 | 3 | Air | Flight |
| RG3 | 2076.47 | 3706 | 219 | 7 | Air | Flight |
| RG5 | 1880 | 140 | 44 | 14 | Air | Longshot |
| RG6 | 4283.62 | 668 | 233 | 14 | Air | Flight |

| # | Reaction |
|---|---|
| 1 | $N_2 + M \leftrightarrow 2N + M$ |
| 2 | $O_2 + M \leftrightarrow 2O + M$ |
| 3 | $NO + M \leftrightarrow N + O + M$ |
| 4 | $NO + O \leftrightarrow O_2 + N$ |
| 5 | $N_2 + O \leftrightarrow NO + N$ |
| 6 | $N + O \leftrightarrow NO^+ + e$ |

# Typical CFD Results




CFD solutions for PG4 (Mach=14, Nitrogen). Normal shock occurring just before the nose increases strongly the pressure and temperature.

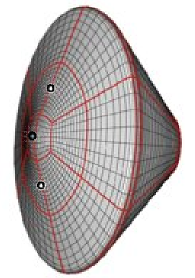
# Errors in density determinations

| Test | Mach | Gas | % Error in ρ | | |
|---|---|---|---|---|---|
| | | | Eq1 | Eq2 | Eq3 |
| PG1 | 2 | Air | 12.4 | 3.5 | 1.8 |
| PG2 | 3 | Air | 6.6 | 2.8 | 2.4 |
| RG2 | 3 | Air | 6.1 | 2.1 | 2.0 |
| PG3 | 7 | Air | 2.7 | 2.2 | 0.4 |
| RG3 | 7 | Air | 3.4 | 1.1 | 1.1 |
| PG4 | 14 | N2 | 1.1 | 1.0 | 3.1 |
| PG5 | 14 | Air | 2.4 | 2.5 | 0.3 |
| RG5 | 14 | Air | 2.6 | 1.7 | 0.45 |
| PG6 | 14 | Air | 2.1 | 2.2 | 2.1 |
| RG6 | 14 | Air | 5.1 | 1.65 | 0.7 |

P: Calorically perfect gas, R: real gases

Solution methods: Calorically Perfect Gas & Newton method (Eq1), Real gas (Eq2, Eq3).

# 3DOF MARS ENTRY ANALYSIS

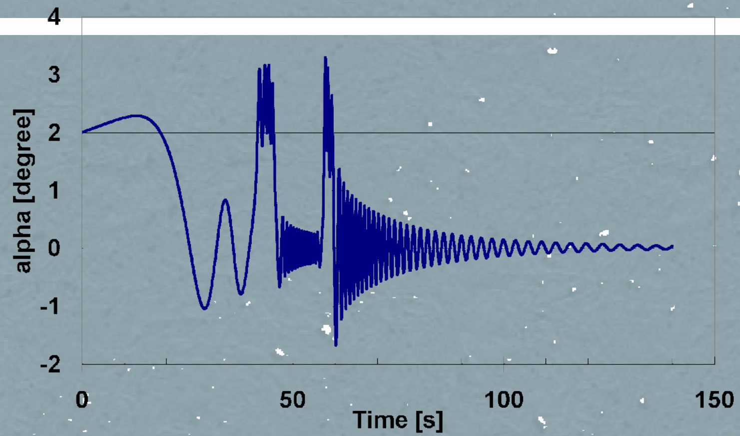


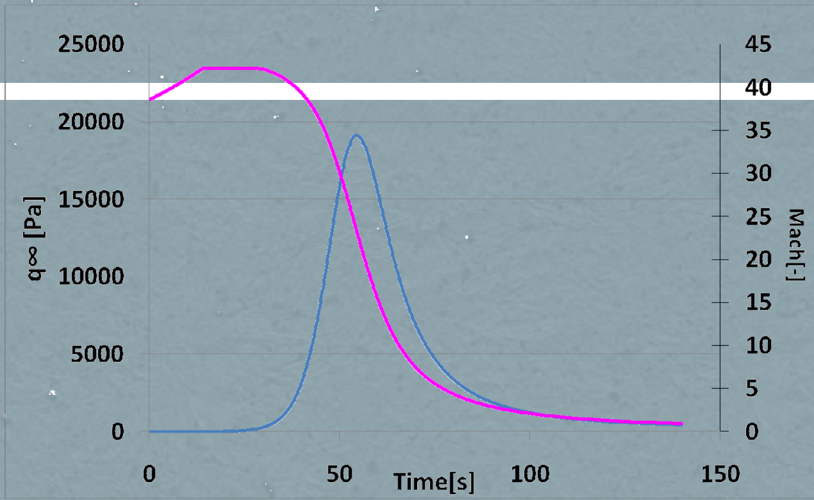
Pathfinder aerodynamic coefficients from Gnoffo et al. 1999, Moss et al 1999. Atmospheric data from MARS-GRAM 2005.

Initial conditions: Entry speed: 7.470 km/s, altitude: = 3522.2 km, angle of attack: 2 degrees, flight path angle : -13.649

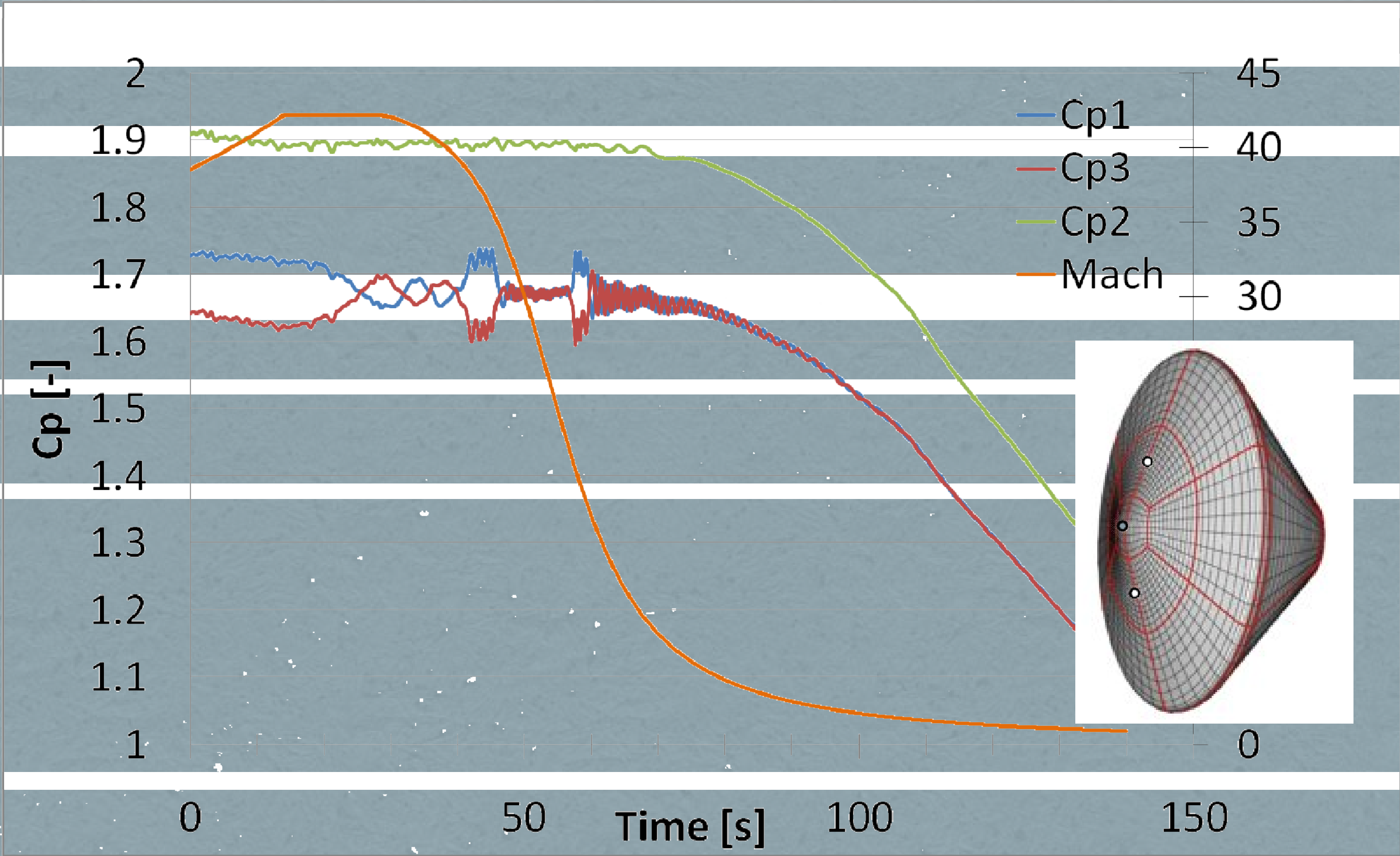
- Methodology:

1- Calculate the attitude, Velocity (dynamic pressure) during the entry.
2- Calculate pressure variations at 3 surface locations using modified Newtonian (with the addition of theoretical mesurment errors).
3- Reconstruct the density profile.

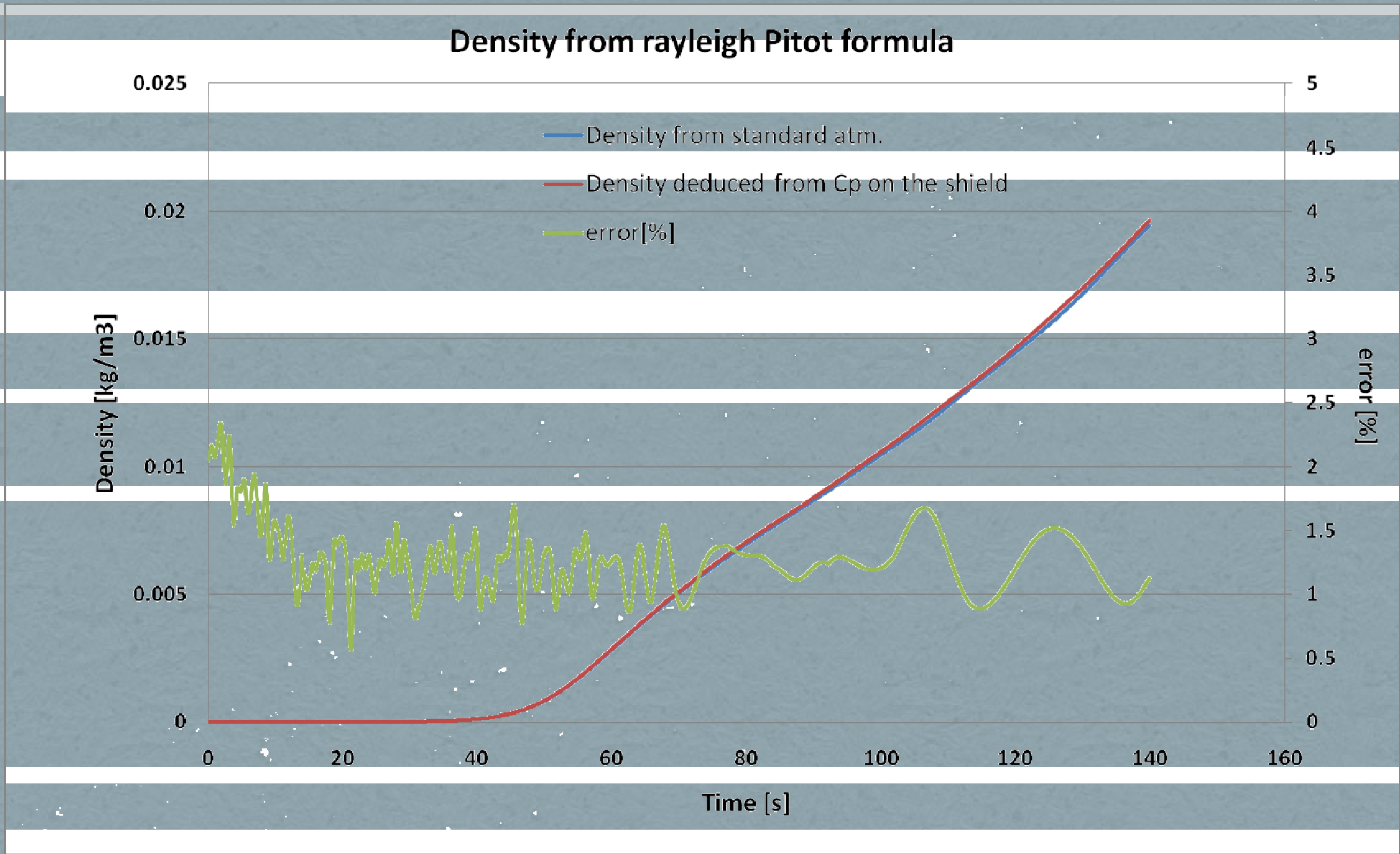


# Surface Pressure Variations



# Density reconstruction



# Conclusions & Perspectives

- Besides validating the aerothermodynamics model multiple pressure measurement is potentially a powerful tool to infer capsule attitude and to reconstruct the atmospheric density profile. The preliminary approach yields few percent error in density reconstruction.

- The presented preliminary approach, specific heat ratio, and free stream velocity are assumed to be known, we did not considered several issues including effects of sideslip angles and spin rate, correction factor $\varepsilon$ (calibration) and validation (wind tunnels and CFD).

- Compared to conventional methods such as accelerometers, multiple pressure measurements can be complementary for density reconstruction *( In conventional methods, the resulting uncertainties are directly proportional to uncertainties in aerodynamic coefficients which can be as high as 4-5%).*